

# Lunar Occultations of Eighteen Stellar Sources from the 2.4-m Thai National Telescope

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## ABSTRACT

We report further results from the program of lunar occultation (LO) observations started at the 2.4-m Thai National Telescope (TNT) in 2014. We have recorded LO events of 18 stellar sources, leading to the detection of four angular diameters and two binary stars. With two exceptions, these are first-time determinations. We could resolve angular diameters as small as 2 milliarcseconds (mas) and projected separations as small as 4 mas. We discuss the individual results, in the context of previous observations when available. The first-time angular diameters for  $\alpha$  Psc, HR 6196 and 75 Leo are in good agreement with expected values, while that of  $\pi$  Leo agrees with the average of previous determinations but has a higher accuracy. We find a new secondary in  $\alpha$  Psc, as previously suspected from Hipparcos data. We also obtain an accurate measurement of the companion in 31 Ari, revealing inconsistencies in the currently available orbital parameters. The TNT, equipped with the fast ULTRASPEC imager, is the leading facility in Southeast Asia for high time resolution observations. The LO technique at this telescope achieves a sensitivity of  $i' \approx 10$  mag, with a potential to detect several hundreds of LO events per year.

*Subject headings:* techniques: high angular resolution – occultations – binaries: general – stars: fundamental parameters

## 1. Introduction

In a previous paper (Richichi et al. 2014b, R14 hereafter) we have described the novel combination of the ULTRASPEC instrument installed at the 2.4-m Thai National Telescope (TNT), and operated in drift mode to achieve fast imaging at the level of few milliseconds. This capability, entirely new for the given longitude range and at a telescope which is the largest in the southeast-asian region, has enabled a program of routine lunar occultation (LO) observations. The aim is to measure angular diameters, to detect and

characterize circumstellar components, and to investigate binary or multiple stars. The achieved angular resolution is at the milliarcsecond level (mas) and the sensitivity  $i' \approx 10$  mag.

This is currently the only routine program of its kind around the world. Another large program was active at the ESO Very Large Telescope in the previous decade and produced a large number of results (Richichi et al. 2014a, and references therein), but was terminated with the decommissioning of the ISAAC instrument. Only few observatories around the world remain suitably equipped to observe LO, and none of them has a comparable program in place. Clearly, the high time resolution of this facility can be employed to observe other classes of objects as well, from cataclysmic variables to transits, and many kinds of transient phenomena.

We report here on LO results recorded in the second TNT observing cycle, between December 2014 and May 2015.

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## 2. Observations and Data Analysis

The observations and the data analysis follow closely what was already described in R14, and we provide here only a brief summary. An in-depth general description of ULTRASPEC at TNT has been presented by Dhillon et al. (2014). For LO, we use the so-called drift mode of the instrument, in which most of the detector is masked and light is recorded in two small square sub-windows. Only one of the two is effectively used. This allows us to record uninterrupted continuous sequences, with typical sampling times around 6 ms and minimal overheads.

For the observations reported here, we have used standard SDSS  $r'$ ,  $i'$ ,  $z'$  broad-band filters, as well as two narrow-band filters,  $R_{\text{cont}}$  and N86. They have central wavelengths of 6010 and 8611 Å and full-width half-maxima (FWHM) of 118 and 122 Å, respectively. Narrow-band filters have the advantage of increasing the contrast of the diffraction fringes, as well of course of reducing the risk of saturation in case of strong lunar background.

We typically record about 30 s data around the predicted time of the event, to account for possible uncertainties, e.g. due to proper motions and limb deviations. The sub-windows can be further rebinned to improve the time resolution – see the parameters Sub and Reb in Table 1.

The result is a sequence of several thousand frames, which are converted to a FITS cube and analyzed with specifically developed software (see Richichi et al. 2014a, and references therein). A crucial step is to adopt an extraction mask tailored to measure only the pixels effectively exposed to the stellar light, thus greatly reducing the noise contribution from the general background. Each frame is accurately time-stamped with sub-millisecond precision thanks to a dedicated GPS signal. Time-stamping is also relevant for other applications such as lunar limb profiling, which however we do not discuss here.

Note that we concern ourselves only with about 1 s of data around the occultation event: the LO diffraction pattern extends in fact over 0.5 s or less. This corresponds in practice to about 2'' on the sky. Thus we are not sensitive to, e.g., wide companions.

We use two approaches to analyze the data: a model-independent maximum-likelihood method to derive the brightness profile of the source (Richichi 1989), and a model-dependent least-squares method to derive parameters such as angular diameters and bi-

nary separations (Richichi et al. 1996). The software includes a number of features, e.g. to derive upper limits for unresolved sources or to model low-frequency scintillation. Details are provided in the references above.

## 3. Results

The LO events are listed in chronological order in Table 1, which follows the same format as R14. In summary: D and R refer to disappearances and reappearances, respectively; the magnitudes and spectra are quoted from Simbad; the filters were described in Sect. 2; Sub and Bin list, respectively, the size of the detector sub-array and the on-chip rebinning - i.e., Sub 16x16 and Bin 2x2 lead to frames of size 8x8;  $\tau$  and  $\Delta T$  are the integration and sampling times, respectively; S/N is the signal-to-noise ratio, measured as the unocculted stellar signal divided by the rms of the fit residuals; and finally UR, Diam, and Bin denote unresolved, resolved diameter, and binary star, respectively.

The stars with a positive determination (i.e., not unresolved) are listed in Table 2, which also follows a format used in our previous papers. Columns 2 and 3 list the measured rate of the event  $V$  and its deviation from the predicted rate  $V_t$ . This deviation is due mainly to slopes in the local lunar limb  $\psi$ , which can thus be retrieved and are listed in Column 4. All the deviations and limb slopes are within the norm, based on the experience of several thousands LO events. Columns 5 and 6 list the Position Angle and the Contact Angle of the event, with the limb slope already included. For the sources found to be resolved, column 7 lists the best-fitting angular diameter in the uniform disk approximation. This is strictly valid for the observed wavelength only; conversions to limb-darkened values can be derived depending on models. For the binary stars, columns 8 and 9 list the projected separation (along the PA direction) and the brightness ratio, respectively.

In the following we discuss in some detail our results, also in the context of available previous studies. We show figures only for one case of a resolved angular diameter (Fig. 1) and for one case of a binary star (Fig. 2).

### 3.1. $\alpha$ Piscium

This star (HR 510, HIP 8198) is a relatively nearby late-type giant star (G8, 85 pc) which has been the

TABLE 1  
LIST OF OBSERVED EVENTS

Date (UT)	Time	Type	Source	V (mag)	Sp	Filter	Sub (pixels)	Bin	$\tau$ (ms)	$\Delta T$	S/N	Notes
09-Dec-14	22:10	R	SAO 97302	8.0	G5V	N86	16x16	2x2	6.6	6.9	5.0	UR
09-Dec-14	22:13	R	SAO 97303	8.7	K0V	N86	16x16	2x2	6.6	6.9	2.6	UR
02-Jan-15	14:53	D	IRC +20090	9.2	K0	N86	16x16	2x2	6.6	6.9	11.9	UR
26-Jan-15	14:14	D	o Psc	4.3	G8III	N86	16x16	2x2	6.1	6.3	60.9	Bin, Diam
27-Jan-15	11:49	D	31 Ari	5.7	F7V	R <sub>cont</sub>	16x16	2x2	6.6	6.9	40.1	Bin
12-Mar-15	20:08	R	HR 6196	4.9	G8II/III	N86	16x16	2x2	6.6	6.9	100.8	Diam
12-Mar-15	20:27	R	SAO 160044	6.7	A3III	$i'$	16x16	2x2	6.6	6.9	85.6	UR
28-Mar-15	14:50	D	SAO 96977	9.3	G0V	$z'$	32x32	2x2	12.4	12.9	6.6	UR, Wide Bin
28-Mar-15	14:50	D	SAO 96978	9.4	G0V	$z'$	32x32	2x2	12.4	12.9	6.0	UR, Wide Bin
30-Mar-15	14:56	D	SAO 98400	6.5	F2Vp	$z'$	16x16	2x2	6.6	6.9	37.2	UR
31-Mar-15	16:00	D	HR 3938	6.0	K3III	N86	16x16	2x2	6.6	6.9	52.7	UR
31-Mar-15	17:47	D	$\pi$ Leo	4.7	M2IIIab	N86	8x8	no	6.1	6.3	146.6	Diam
24-Apr-15	14:33	D	SAO 96634	9.0	A2V	$r'$	32x32	no	25.1	25.6	21.8	UR
29-Apr-15	17:32	D	75 Leo	5.2	M0III	N86	16x16	no	11.9	12.2	266.9	Diam
30-Apr-15	17:36	D	SAO 138554	8.5	K2	$z'$	16x16	2x2	6.6	6.9	21.3	UR
07-May-15	19:10	R	SAO 161004	7.5	O9.2IV	N86	16x16	no	11.9	12.2	4.3	UR
08-May-15	17:55	R	IRC -20529	9.4	M4	N86	16x16	2x2	6.6	6.9	32.1	UR
11-May-15	20:55	R	SAO 164693	7.5	G0	$z'$	8x8	no	6.1	6.3	61.6	UR

TABLE 2  
SUMMARY OF RESULTS: ANGULAR SIZES (TOP) AND BINARIES (BOTTOM)

(1) Source	(2) V (m/ms)	(3) (V/V <sub>t</sub> )-1	(4) $\psi(^{\circ})$	(5) PA( $^{\circ}$ )	(6) CA( $^{\circ}$ )	(7) $\phi_{UD}$ (mas)	(8) Proj.Sep.(mas)	(9) Br. Ratio
o Psc	0.2138	-4.6%	-0.8	144.2	73.8	2.17 $\pm$ 0.01		
HR 6196	0.4345	12.3%	4.9	345.9	231.1	1.85 $\pm$ 0.01		
$\pi$ Leo	0.6112	-7.5%	-11.3	121.7	27.3	4.35 $\pm$ 0.01		
75 Leo	0.6695	-0.8%	-1.5	132.5	18.5	2.94 $\pm$ 0.03		
o Psc	0.2138	-4.6%	-0.8	144.2	73.8		12.4 $\pm$ 0.4	41.1 $\pm$ 0.3
31 Ari	0.2730	-4.9%	-1.5	307.5	60.5		3.76 $\pm$ 0.02	1.52 $\pm$ 0.02

subject of several investigations concerning its possible binary nature. It was included in a catalog of stars whose Tycho and Hipparcos data showed non-linear behavior with time, indicating possible astrometric binaries (Makarov & Kaplan 2005). As such, it was also included as possible binary in a catalog of bright multiple systems by Eggleton & Tokovinin (2008). Frankowski et al. (2007) did not find evidence of changes in the radial velocity, using a statistical analysis that was however mostly sensitive to stars with parallax  $> 20$  mas. Hartkopf & McAlister (1984) obtained speckle observations at a 4-m telescope, finding it unresolved with an upper limit of 30 mas. Interestingly, no LO event of this star was ever reported until now.

We obtained a good quality ( $S/N=61$ ), first ever LO light curve of  $\alpha$  Psc. Thanks to a relatively large contact angle, the effective limb velocity was about 3 times slower than normal, leading to an increased sampling of the fringes which was crucial in assessing departures from a point source. The data are consistent with a resolved angular diameter and in addition with a secondary component 4.0 mag dimmer than the primary, with a separation of 12 mas projected along  $PA=144^\circ$ . Our first-time determination of the angular diameter, when combined with the Hipparcos distance, results in  $19.8 R_\odot$ .

The companion, given the magnitude difference, is likely to be a main sequence star, although more details could be ascertained only with further observations at different wavelengths. Some constraint on the actual PA can be inferred from the upper limit on the separation by Hartkopf & McAlister (1984). Assuming that their speckle measurements were sensitive to a companion with such a brightness ratio, the PA would have to be in the –admittedly broad– range  $78^\circ$  to  $210^\circ$ . Assuming a combined  $1 M_\odot$ , a real separation between 1 and 2.6 AU (converted from our measurement and from the speckle upper limit), a circular orbit and no inclination effects, the minimum period would be between 1 and 4 years. Barring significant inclinations of the orbital plane on the sky, orbital motion might be detectable within relatively short periods of time, using i.e. adaptive optics at a very large telescope at visual wavelengths.

### 3.2. HR 6196

This star is a late-type giant (G8II/III) and a bright near-infrared source (IRC –20325,  $K = 2.1$  mag). No

angular diameter measurements are present in the literature. Evans & Edwards (1981) obtained a LO light curve, finding the source unresolved. Their data were recorded in the blue with a small telescope and were presumably noisy. Another previous LO light curve is listed in the CHARM2 catalog (Richichi et al. 2005), however the result was not published. Pasinetti Fracassini et al. (2001) estimated a diameter of 2.0 mas.

We recorded a high S/N reappearance light curve of HR 6196. The data are best fitted by a resolved source model of 1.85 mas diameter, which leads to a  $\chi^2$  almost 2.5 times lower than for a point source. We also revisited the old data set mentioned in CHARM2, which was obtained with an InSb photometer in the  $K$  band at the Calar Alto 1.2-m telescope on July 16, 1997. Unfortunately, those data are affected by significant scintillation and only lead to an upper limit between 2.7 to 3.4 mas, consistent with our result but not very constraining.

### 3.3. $\pi$ Leonis

This cool giant (HR 3950, IRC +10224) has had a number of spectral classifications, with a general agreement around M2. It has featured in many publications especially in the near-IR, where it has often been used as a calibrator source due to its brightness ( $K = 0.5$  mag) and minimal variability (e.g. Monnier et al. 2004; Woodruff et al. 2008; Montargès et al. 2014).

The angular diameter of  $\pi$  Leo has been repeatedly determined in the past, with results listed in the uniform  $\phi_{UD}$ , limb-darkened  $\phi_{LD}$  or fully-darkened  $\phi_{FD}$  disk hypothesis. Using the NPOI interferometer at various wavelengths with an average of 740 nm, Nordgren et al. (1999) reported  $\phi_{UD} = 4.29 \pm 0.05$  mas, in very good agreement with our own determination. A large number of LO observations also exist, with varying levels of data quality and accuracy. Vilas & Lasker (1977) reported  $\phi_{LD} = 5.9$  mas in the  $R$ -band (no error), while Africano et al. (1978) reported  $\phi_{FD} = 3.9 \pm 1.0$  mas in the blue. We note that in both cases a small sub-meter class telescope was used, so that scintillation may have played a role. A "smoothing procedure" was claimed as a possible cause for the first high value (Africano et al. 1978). Later, Ridgway et al. (1979) reported  $\phi_{UD} = 4.58 \pm 0.33$  mas, while Baug & Chandrasekhar (2013) obtained  $\phi_{UD} = 4.9 \pm 0.5$  mas, both in narrow  $K$ -

band filters. Schmidtke & Africano (2011) reported  $\phi_{UD} = 3.85 \pm 0.15$  mas, using a 1991 LO light curve obtained in  $H_\alpha$  with a 1.3-m telescope. The weighted average of these LO results, neglecting the difference in wavelengths and limb-darkening, gives at first approximation  $\phi = 4.3 \pm 0.3$  mas.

We obtained a light curve for  $\pi$  Leo with a quality (S/N=147) better than any previous others. As shown in Fig. 1, the source is clearly resolved, and our result listed in Table 2 is consistent with all good-quality previous determinations, but with significantly improved accuracy.

### 3.4. 75 Leonis

This is a bright M0 giant (HR 4371), especially luminous in the near-IR (IRC +00203,  $K = 1.4$  mag) and included in many publications, some of which covering high-angular resolution. Despite several attempts, the star had remained until now essentially unresolved. These include speckle observations at a 4-m telescope with a stated upper limit of 35 mas by McAlister et al. (1989) and by Mason (1996), and a three-channel LO light curve from a 1.5-m telescope by Meyer et al. (1995). Guhl & Stecklum (1991) obtained a LO light curve which was consistent with a companion at a projected separation of 45 mas and 0.8 mag fainter. However, the data were obtained with a 40-cm telescope in an urban environment and the authors themselves cautioned about this finding. Having a stable luminosity, the star has also been included in catalogs of spectrophotometric indirect diameter estimates. For example, Cohen et al. (1999) quote  $\phi_{UD} = 2.90 \pm 0.03$  mas.

Our light curve for 75 Leo has a formally very high S/N of 266. In fact, the data were taken with a rather slow sampling (and correspondingly long integration time, hence the high S/N value), due to passing clouds that made the star temporarily disappear during acquisition and forced us to observe in blind mode with an unusually large sub-window. As a result, the diffraction fringes are smoothed and poorly sampled. Nevertheless, these factors can be properly included in the data analysis and the  $\chi^2$  clearly shows that the star is indeed resolved. Our resulting angular diameter value is  $\phi_{UD} = 2.94 \pm 0.03$  mas, in excellent agreement with the estimate of Cohen et al. (1999). This represents the only direct determination for 75 Leo. Barring a very unfavorable combination of projection directions, the bright companion possibly claimed by (Guhl & Stecklum 1991, who did not mention a PA for

their event) should have been seen in our data.

### 3.5. 31 Ari

This bright star (HR 763, SAO 93022) has a spectral type F7V. Being main sequence, it is as expected relatively nearby: its Hipparcos parallax places it at 35 pc. 31 Ari was first discovered to be binary from a LO by Africano et al. (1978), with projected separation 21 mas along PA=265.7. The magnitude difference was found to be small both in the blue and in the red, prompting the authors to speculate similar spectral types. For comparison with our measurement (shown in Fig. 2), they quoted  $\Delta\text{mag} = 0.3 \pm 0.1$ .

Following up on this, 31 Ari was detected as binary using speckle by McAlister & Hendry (1982), and later reported in numerous other publications. Both Balega & Balega (1988) and Mason (1997) computed orbital elements. They are however in considerable disagreement. Using the latest, and presumably more complete, of the two we find that both older (e.g. Africano et al. 1978; Hartkopf et al. 2000, epochs 1977.75 and 1984.07) and newer observations (e.g. Hartkopf et al. 2012; Horch et al. 2012, epochs 2010.96 and 2009.75) cannot be reproduced. It is thus not surprising that also our measurement is at odds with the PA and separation predicted for epoch 2015.07 using the elements by Mason (1997). Clearly, a reevaluation of all available measurements for 31 Ari is needed.

### 3.6. Other sources

IRC+20090 was found to have  $\phi_{UD} = 3.7 \pm 0.3$  mas by Tej & Chandrasekhar (2000) from a LO event in the near-IR. The S/N in our light curve is insufficient to measure the angular diameter.

The two stars SAO 96977 and SAO 96978 are the components of the wide binary system ADS 6146. We recorded both LO events inside the same sub-window, about 5 s apart, and we treated them separately. Both were found to be unresolved.

The bright star SAO 98400 (HR 3635) is an intriguing case. It was claimed as a possible double, seen in two colors simultaneously, by Eitter & Beavers (1979). They mentioned strong noise in their data and did not provide details about the separation, but they quoted a private communication from another observer who had also detected SAO 98400 as binary. Using speckle at a 4-m telescope, McAlister et al. (1989) detected the companion with 89 mas separation along

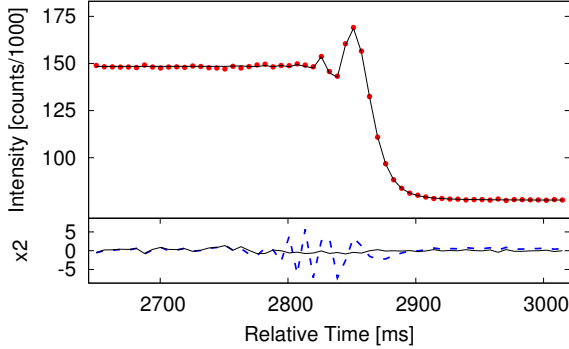


Fig. 1.— Top panel: occultation data (dots) for  $\pi$  Leo, and best fit by a model with an angular diameter of 4.35 mas (solid line). The lower panel shows the fit residuals, enlarged by a factor of two for clarity, as a solid line. For comparison, also the residuals of the best fit by a point-like source are shown (dashed line). A color version of this figure is available online.

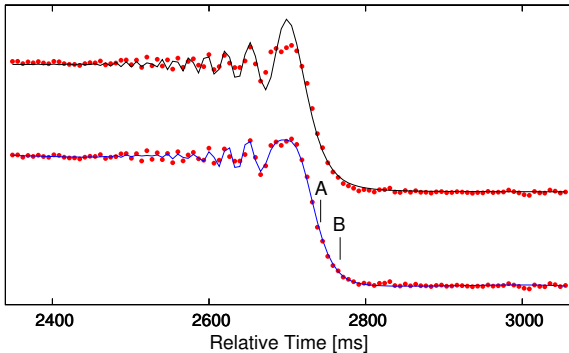


Fig. 2.— The occultation data (dots) for 31 Ari, repeated twice and offset for clarity. The top set shows the best fit by a point-source model, and the bottom set the best fit by a binary model with 3.76 mas separation. The two segments mark the times of the geometrical occultation of each component. The vertical axis is in arbitrary units. A color version of this figure is available online.

PA=  $71^\circ$ . Following that however, the source was not detected again by speckle in several attempts including with the Russian 6-m telescope (McAlister et al. 1993; Balega et al. 1994; Fu et al. 1997). The star is at just under 40 pc distance and one could speculate a highly eccentric orbit which over the course of a few years brought the component below the diffraction limits of the telescopes employed. We note that our LO light curve had sufficient S/N and sampling rate to detect the companion if the projected separation had been  $\gtrsim 5$  mas.

SAO 96634 was reported as binary from visual micrometer observations by Couteau (1966, 1975), with separation 71 mas and PA=  $43.8^\circ$ , unchanged over nine years. The system was rediscovered by Africano et al. (1978, apparently unaware of Couteau’s work) who recorded two LO events, each in two colors. The projected separations ( $0''.3$  and  $0''.2$ ) however did not agree with Couteau’s results, and also not between themselves. Finally, Mason (1996) could not resolve the system by speckle observations at a 3.6-m telescope. Our data are consistent with a companion with 60 ms projected separation along PA=  $85^\circ$ , in approximate agreement with Couteau’s values. However, we do not list this among our binary detections because there is no significant  $\chi^2$  improvement over a point-source model. The companion should be detectable by adaptive optics imaging.

#### 4. Conclusions

We reported the latest results from the program of routine LO observations at the 2.4-m Thai National Telescope. They include 4 angular diameters, three of which are first-time determinations, and two binary stars, of which one was not previously known.

The angular diameters of  $\alpha$  Psc, HR 6196,  $\pi$  Leo and 75 Leo are found to be in the range 2 to 4 mas, with an average accuracy of 0.5%. Thus, if combined with accurate bolometric fluxes, our results have the potential to constrain the effective temperatures to the 1% level, or less than 50 K. Concerning the binary stars, we detected companions with projected separations of about 4 and 12 mas in 31 Ari and  $\alpha$  Psc, respectively. The magnitude differences (in one case as high as 4 mag) could be measured to the 1% level.

We also discussed those stars for which an angular diameter or a companion had been previously published, but which we found unresolved. The case of SAO 98400 merits attention, as this binary was de-

tected repeatedly in the 1980's but not in the following decades.

As stated in R14, the TNT equipped with the ULTRASPEC EMCCD fast imager can record LO light curves with few ms sampling times to about  $i' \approx 10$  mag at S/N=1. For illustration, we computed future events taking the SAO catalog as an approximate proxy for the sample of stars potentially reachable by LO at the TNT. After filtering for good circumstances (Sun and Moon elevations, lunar phase), we find that over 500 LO events would be well observable during each dry season period.

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